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RESEARCH DEPARTMENT



REPORT

# **Field store standards conversion: equalisers for ultrasonic quartz delay lines**

**No. 1971/36**



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QUARTZ DELAY LINES**

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Head of Research Department

(EL-54)



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## FIELD STORE STANDARDS CONVERSION: EQUALISERS FOR ULTRASONIC QUARTZ DELAY LINES

### Summary

*A field-store standards converter has been built which uses fused quartz delay lines as the storage medium for the television signal. The associated amplifiers, which have been described elsewhere,<sup>1</sup> contain equalisers which allow the gain and group-delay to be adjusted so that the overall delay-unit response lies between very close, specified, limits. The present report describes the design and adjustment of a novel form of active equaliser and the development of equipment for the detailed examination of the responses of the delay-unit.*

### 1. Introduction

Ultrasonic quartz delay lines have many applications in television: references to these and, in particular, a description of the amplifiers used in the quartz delay units of a field-store standards converter have already been given in an earlier report.<sup>1</sup> Although some of that description is repeated here, this report concentrates on the problems of accurately equalising the gain and delay of quartz delay units and discusses the philosophy and techniques of equalising a large number of different units.

As described in the earlier report<sup>1</sup> the conversion process involves the systematic switching, singly and in groups during each television field, of up to twenty cascaded delay units in the signal path. This switching operation creates a special problem in that small and otherwise unimportant differences in performance between individual delay lines become noticeable as patterns on the converted picture. Ultrasonic quartz delay lines operate at radio frequency and the television signal must be modulated on to a carrier<sup>1</sup> in order to pass through them; frequency modulation of this carrier is used in the standards converter to avoid the patterning which would otherwise result from any small gain differences between the individual delay units.<sup>2</sup> Even using frequency modulation, however, the converted picture may still show patterns which are caused by differences in the frequency-dependent delay or gain characteristics of the units, and this necessitates very careful equalisation.

It was estimated that, if the defects in the delay lines were correlated in the most unfavourable way, then the overall picture impairment could be made acceptable only by equalising the gain and delay responses of each delay unit to within  $\pm 0.2$  dB and  $\pm 4$  ns, respectively, over a frequency range of from 25 MHz to 35 MHz; this was therefore accepted as a target specification.

### 2. Response limitations

Response limitations arise from the characteristics of (a) the fused quartz delay line itself,<sup>3,4</sup> (b) the transducers<sup>3,4</sup> and (c) the external circuits; these items are given in the order of increasing accessibility for adjustment.

Taking these in turn, the loss and delay in the quartz are both functions of the temperature and require a very stable high-temperature environment; in addition the finite thickness of the quartz plate, and imperfections in the material from which it is made, may introduce undesirable ripples in the responses. The transducers and their mechanical tuning and damping account for most of the loss in the delay line and determine the limits of the pass-band. The specification<sup>4</sup> of a delay line and its transducers usually allows broad limits to the response variations within a stated pass-band, recognising that it would be impracticable to achieve the ultimately-desired uniformity without individual equalisation in the external amplifiers. The purpose of these amplifiers is to raise the signal to a high level at the input transducer, to retrieve it from a low level at the output transducer and to equalise the response to give a uniform-delay, unity-gain unit.

At the input transducer, the problem is to maintain a large signal-voltage across the capacitance of the transducer without bandwidth restriction, group-delay distortion or non-linearity. Fig. 1 shows the wide-band matching network employed. This network provides no equalisation but, by resonating the input transducer at 30 MHz and providing suitable reactance compensation, it matches the input transducer to the input amplifier with less than 0.1 dB mismatch loss over the band from 24 MHz to 38 MHz.

The signal at the output transducer is fed to a pre-amplifier whose input impedance is approximately 50 ohms and which is mounted as close to the transducer as possible. This arrangement has been found to provide sufficient bandwidth and adequate signal/noise ratio.

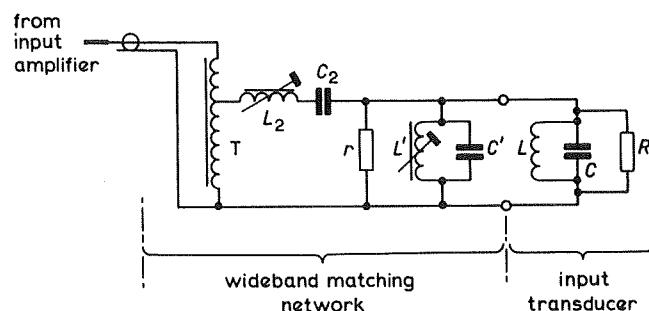


Fig. 1 - Matching at input transducer

### 3. Philosophy of equalisation

Consideration of equalisation leads to two different methods of attacking the same problem. Equalisation involves two sequential operations, namely the measurement of the unequalised response of the network followed by the synthesis of a network with a suitable complementary response using a limited number of variables. There are two ways of performing each operation. The measurement may be either a set of numbers suitable for a computation or a display showing the response in graphical form. The synthesis may take the form of another set of numbers, for example, the computed values of components in an exactly optimal equaliser circuit, or it may avoid computation and evaluation by using a process of repeated adjustment of uncalibrated variable components until the desired overall response of network and equaliser is achieved by inspection and approximation.

The two alternatives for each operation may clearly be paired to form two alternative methods. The first involves measurement, computation and synthesis; the second involves display and empirical approximation. It will be clear that, although both methods require the same accuracy of measurement, the empirical method demands a fairly sophisticated display. It may not be so clear that the two methods tend to favour different types of equaliser; the reasons for this difference are as follows.

If an equaliser is computed, the computation may be arranged to satisfy many conditions simultaneously and may therefore automatically absorb the losses in each equaliser and maintain optimum interface conditions in a cascade of equalisers so as to prevent interaction between them. In this case, the most satisfactory type of equaliser will have a simple, passive circuit, such as the classical bridge-T network.

If, on the other hand, the equalisation is empirical, the most satisfactory type of equaliser will possess a just-sufficient number of variable components such that each controls one feature of the displayed response independently of the remaining variables and of other equalisers. To achieve this independence with a passive network would require variable components to be ganged together in a very complex way. An active network, however, offers the great advantages of unidirectional coupling and loss retrieval; so that an active equaliser can be designed to have simple independent controls.

The second, empirical approach has been chosen here and a design of active equaliser has been developed<sup>5,6</sup> which has a greater flexibility and tolerance of component values than its classic, passive equivalent. In order to facilitate the adjustment of such equalisers, equipment for displaying their amplitude and delay responses was also developed; this is described in Section 5.

### 4. Adjustable equaliser circuits

#### 4.1. Active all-pass networks

Active all-pass networks were described in 1964<sup>5</sup> by Kiefer of IRT in connection with equalisation of vestigial-sideband filters and this led to some unpublished work in 1965 by J.B. Izatt of BBC Research Department. The

types of equaliser used in the field-store standards converter may be regarded as extensions and simplifications of Izatt's networks.

Simplified circuit diagrams, vector diagrams and frequency responses of the group delay and amplitude equalisers are shown in Fig. 2 and Fig. 3 respectively and will be described in the following sections. Both types of equaliser depend for their operation on the properties of a single tuned LC circuit and they have four adjustments which control centre frequency, bandwidth, amplitude and symmetry. They are designed to be cascaded so that the low input impedance of one equaliser provides the preceding equaliser with the low-impedance load necessary for current addition and isolation. The simplicity of the circuits, their relatively low Q value and the limited range of adjustment make for a design of equaliser which is stable, rugged and even elegant.

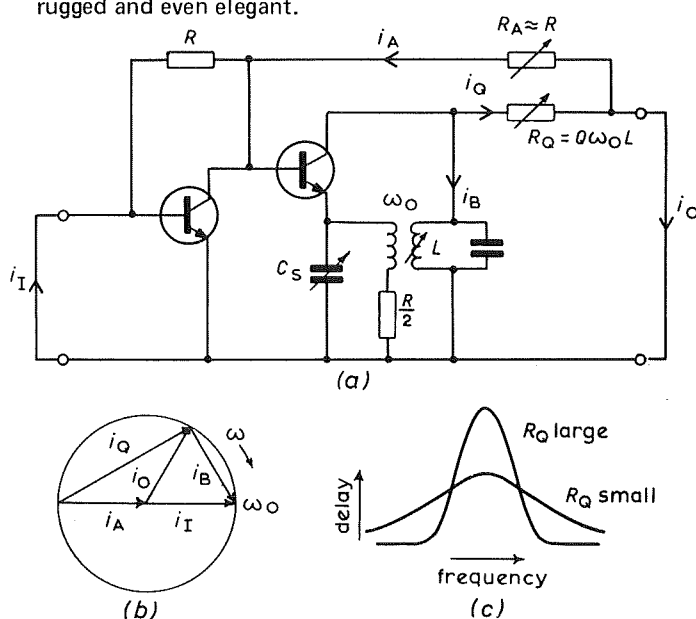


Fig. 2 - Active group-delay equaliser

(a) Circuit (b) Vector diagram (c) Response

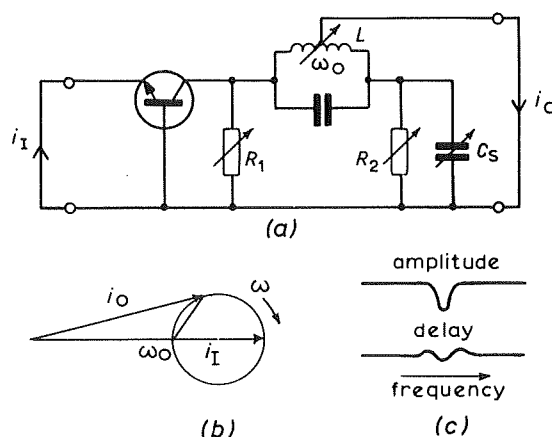
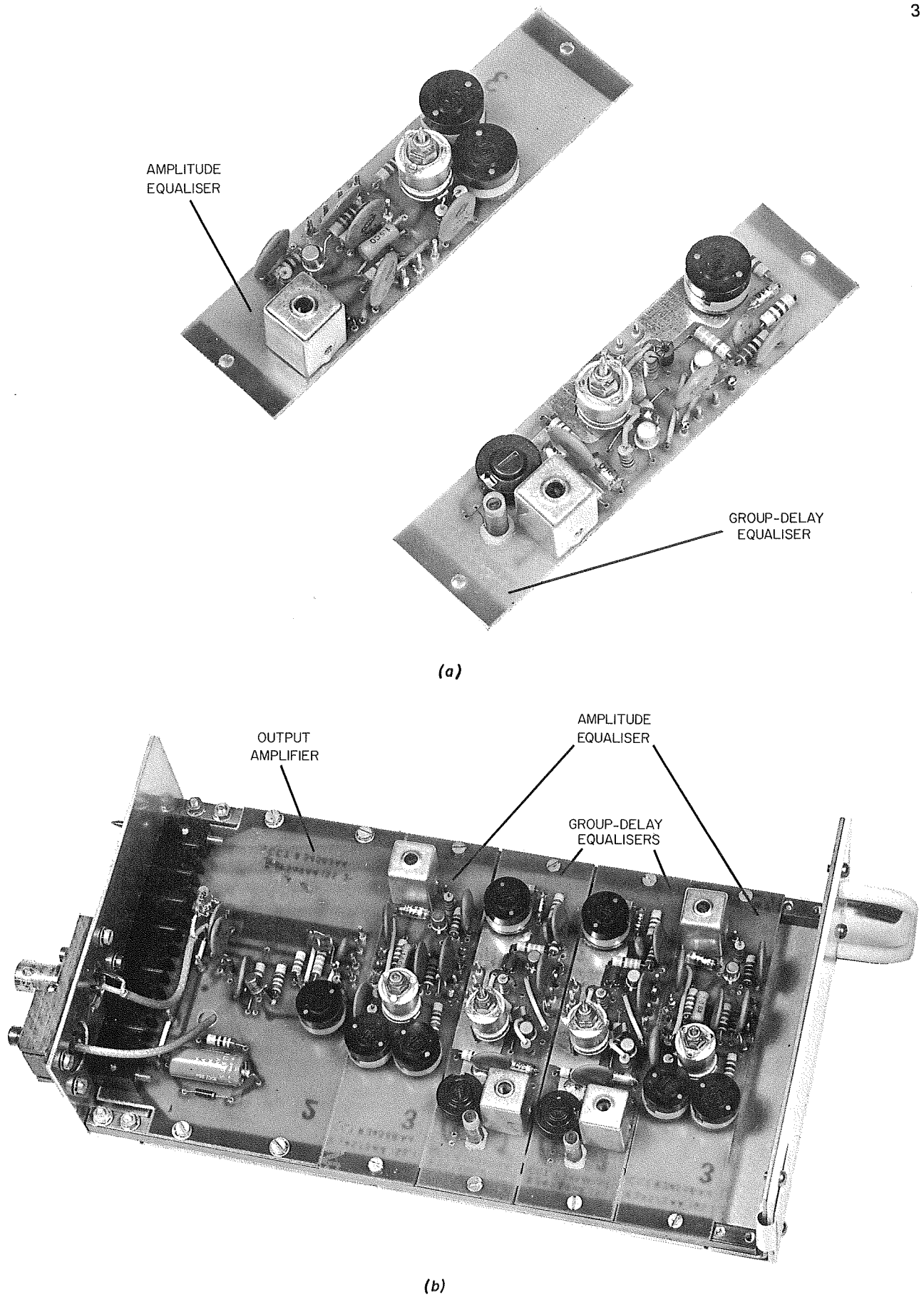


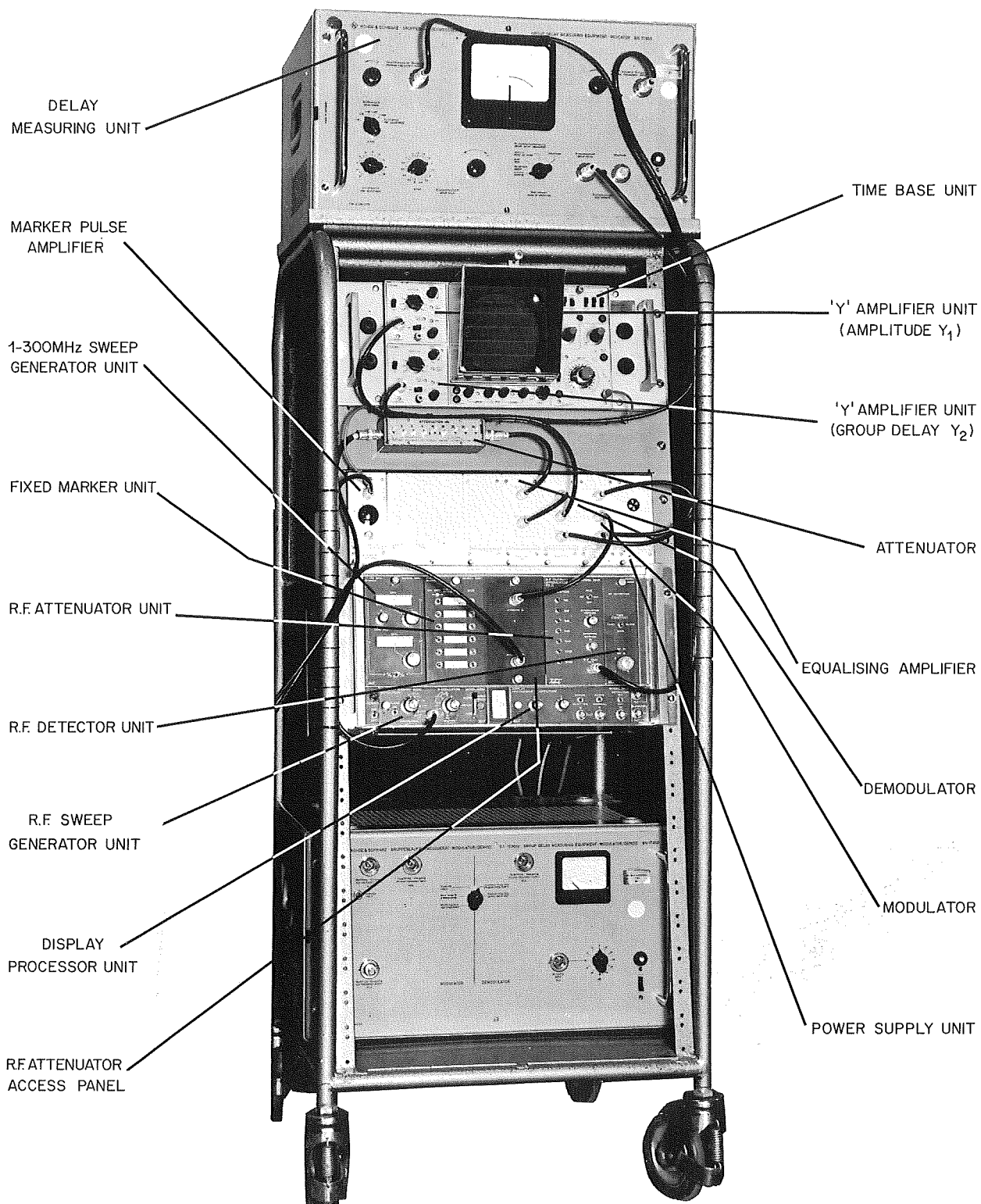
Fig. 3 - Active amplitude equaliser

(a) Circuit (b) Vector diagram (c) Response

The units were mounted on narrow printed-circuit cards, as shown in Fig. 4(a), so that a suitable combination of both types of unit could be chosen and cascaded to form the composite output amplifier as shown in Fig. 4(b).



*Fig. 4 - Amplitude and group delay equalisers forming composite output amplifier*  
 (a) Amplitude and group delay equaliser sub-units      (b) Composite output amplifier



*Fig. 5 - Simultaneous amplitude and delay indicating equipment*

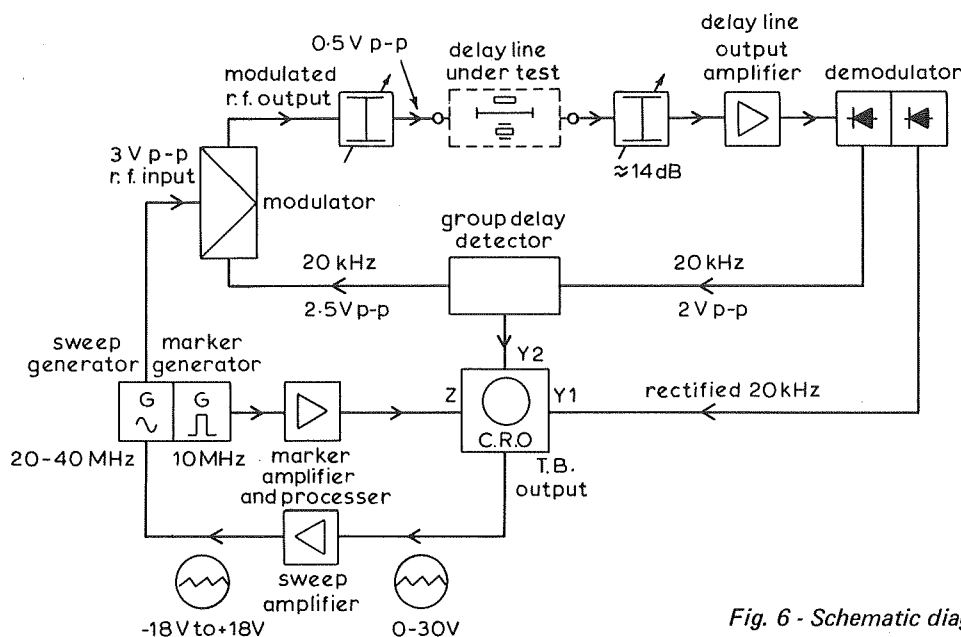


Fig. 6 - Schematic diagram of SADIE

## 4.2 Group delay equaliser

In the group delay equaliser (Fig. 2(a)), the tuned LC circuit is current-fed and its Q-factor is determined by the variable resistor  $R_Q$ . The current through  $R_Q$  has a circular vector-locus with the origin on the periphery (Fig. 2(b)); by adding to this current another current, through  $R_A$ , equal and opposite to the input current, the origin is moved towards the centre of the circle. The combined current vector then becomes a radius of the circle and the circuit has all-pass properties with a maximum phase slope at the resonant frequency,  $\omega_0$ , and a maximum group delay  $T = 4Q/\omega_0$ ; (Fig. 2(c)). By varying  $R_A$  about a mean value,  $R$ , the amplitude response may be made to rise or fall symmetrically about  $\omega_0$ ; it may also be given a skew-symmetrical component by adjusting  $C_s$ . The natural loss of the LC circuit itself is cancelled by a small amount of positive a.c. feedback provided by the coupling coil; this is pre-set and ensures that the amplitude response at  $\omega_0$  is independent of  $R_Q$ , which controls the peak group-delay. The four variables then give independent control of the centre-frequency ( $L$ ), the peak group delay ( $R_Q$ ), the amplitude lift or depression ( $R_A$ ) and the symmetry ( $C_s$ ). With a maximum value of Q factor of five, the maximum group delay near 30 MHz is about 100 ns, falling to 50 ns at  $\pm 3$  MHz; this has been found to be an adequate maximum value for equalisation of the quartz delay units.

## 4.3 Amplitude Equaliser

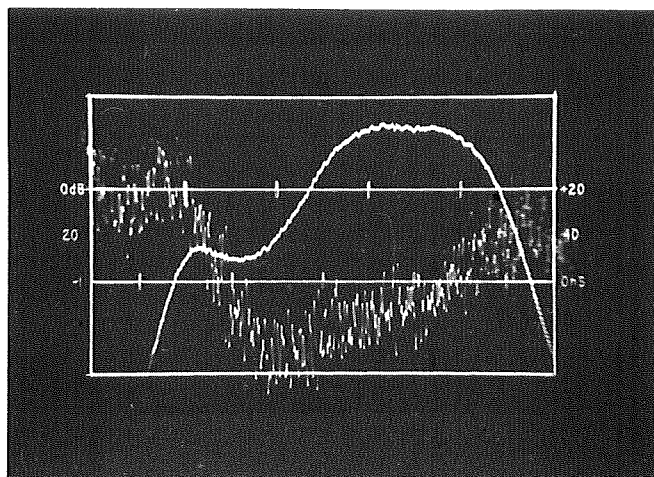
In the amplitude equaliser (Fig. 3(a)) the tuned LC circuit is centre-tapped so that the two resistors  $R_1$  and  $R_2$  carry antiphased currents each having a vector locus similar to that described for the group delay equaliser. If these two resistors are equal in value and if the capacitor  $C_s$  is equal to the transistor capacitance, the response of the circuit will be flat in amplitude and phase and the circle in the vector diagram of Fig. 3(b) will vanish. If, however, the resistors are unbalanced, the difference between their currents will be carried by the load and the response will

rise or fall in the vicinity of  $\omega_0$ , depending on the direction and degree of unbalance; skew-symmetry may be introduced by changing  $C_s$  as before. The Q-factor of the tuned circuit is also controlled by varying the two resistors; the interdependence of amplitude and Q controls could be avoided by extra complication but is not intolerable. The group delay is minimal; for a given value of Q, and an amplitude range of 1 dB, the amplitude equaliser gives a maximum group delay of only 5% of that of the group delay equaliser. Using a Q-factor of up to about 12, amplitude equalisers of this type are most useful in removing the effects of imperfections in the material of the quartz delay lines provided that the response fluctuations are no greater than about 1 dB.

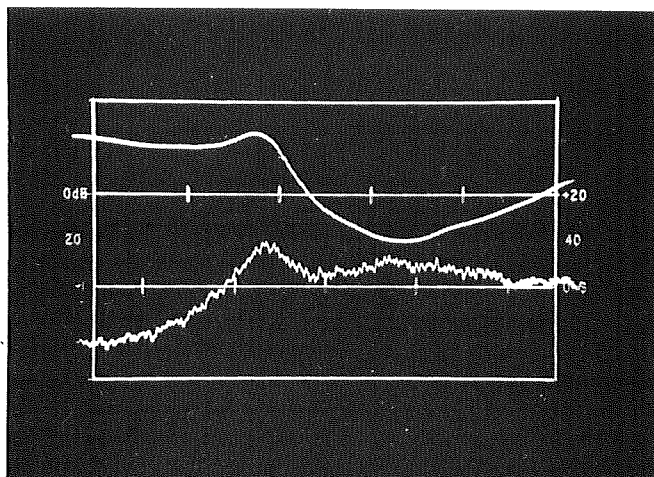
# 5. Equalising techniques

## 5.1 Display equipment

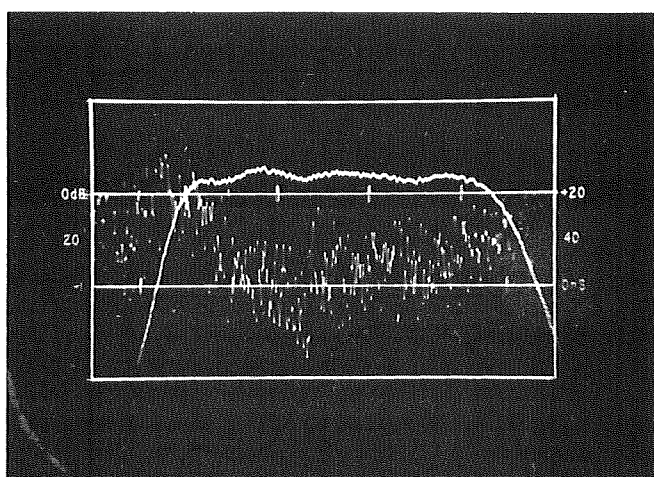
Having chosen to adjust the delay unit equalisation empirically, it was therefore necessary to observe the responses throughout the process of adjustment. This led to the construction of the Simultaneous Amplitude and Delay Indicating Equipment (SADIE) of which Fig. 5 is a photograph and Fig. 6 a schematic diagram. SADIE's operation is basically simple: a carrier signal is repeatedly swept from 20 MHz to 40 MHz carrying amplitude modulation at 20 kHz; the group delay response is obtained by comparing the phase of the output signal envelope with that of the original modulating signal; the amplitude response is obtained by measuring the demodulated signal output level. These two responses are displayed simultaneously on a double-beam oscilloscope with a long-persistence tube. The equipment affords a phase discrimination of the order of 0.01 degree at 20 kHz (group-delay discrimination better than 2 ns); a separate demodulator for the 20 kHz signal was built to provide an amplitude discrimination of  $\pm 0.1$  dB.



(a)



(b)



(c)

**Fig. 7 - SADIE responses during equalising process**

upper trace : amplitude                      lower trace : group delay  
frequency markers at 2 MHz intervals

- (a) Response of delay line before equalising
- (b) Response of two equalisers;  
at 27 MHz, amplitude equaliser with lift and skew;  
at 33 kHz, group delay equaliser with  
amplitude depression
- (c) Response of delay line with equaliser as in (b)  
showing need for further group delay equaliser

The swept-carrier generator had to be capable of very slow sweep rates (less than one per second) so that the responses would not be distorted either by the time constant of the 20 kHz phase detector or by the time delay of the unit being tested; this is 3.3 ms for the longest unit and up to 20 ms for the group forming a television field delay.

## 5.2 Empirical equalisation

### 5.2.1 General

Before a delay unit is assembled, the quartz delay line must pass a series of tests to check that it meets a specification agreed with the manufacturer. In one of these tests the amplitude/frequency response of the delay line is measured, at the operating temperature, and this is specified as the ratio of the output voltage, across a 50-ohm load resistor, to the input voltage. This response may show slow variations with frequency, up to the 3 dB limit set by the specification.

When the delay unit is fully assembled, the 50-ohm load resistor used for the above measurement is replaced by the 50-ohm input impedance of the output pre-amplifier and the response frequency characteristic of this part of the unit is unchanged. A change to the overall amplifier/frequency response is caused, however, by the matching network at the input transducer. The bandwidth over which equalisation was to be within the specification was, for the earlier units, 25 MHz to 35 MHz; for the present design, which operates with a double sideband signal,<sup>1</sup> the equalised bandwidth was increased to 24 MHz to 38 MHz.

### 5.2.2 Final adjustment

The output amplifier, following the output pre-amplifier, raises the signal level from 150 mV to 0.5V peak-to-peak and contains up to four of the equalisers described in Section 4.2 and 4.3 and illustrated in Fig. 4. These equalisers must now be chosen and adjusted to bring the responses of the delay circuit within the target specification of  $\pm 0.2$  dB and  $\pm 4$  ns over the frequency range 25 MHz to 35 MHz. The required number and type of equalisers is determined by inspection of the amplitude and group-delay responses of the partly-assembled unit, using SADIE or similar equipment, and with a knowledge of the range of responses provided by the two types of equaliser sub-units. The process of selection and adjustment requires some experience on the part of the operator; this is best illustrated by describing the partial equalisation of a typical delay unit with the help of photographs of the responses shown in Fig. 7.

Fig. 7(a) shows the responses of a delay unit after being fully assembled, but before equalisation, as displayed on the oscilloscope of SADIE. The graticule has two vertical sides and nine intermediate vertical marks representing 2 MHz intervals from 20 MHz to 40 MHz; there are four horizontal lines representing, on the left-hand scale, 1 dB intervals in amplitude and, on the right-hand scale, 20 ns intervals in the delay. The group-delay response is distinguished by the greater 'fine structure'

which, although looking like random noise, is closely related to the fine structure in the amplitude response and is a function of the frequency, being caused by very low level multipath propagation in the quartz. The fine structure is insignificant in the performance, is ignored in the equalisation and may be filtered before display, if desired. The response of the delay line shows the following more important defects:

- (i) Narrow amplitude droop at 27 MHz
- (ii) Broad group-delay droop at 30 MHz
- (iii) Broad amplitude lift at 33 MHz.

An amplitude equaliser would be selected for (i) and a group-delay equaliser which would at least partially correct (ii) and (iii). By fitting and adjusting these two equalisers to have the response of Fig. 7(b) (though this response is not normally examined) the overall response may be optimised as shown in Fig. 7(c). Clearly, before the specification is met, there is a need for a second group-delay equaliser tuned near to 30 MHz, followed by further adjustments of the first, but the desired end is in sight.

The number of these equalisers required to bring a delay unit within the target specification has been found to be between one and five. Since the standard output amplifier can accommodate up to only four equalisers, an extra output amplifier would be needed for units with five equalisers. In practice the need for a fifth equaliser and extra amplifier can be avoided by relaxing the group delay specification to  $\pm 10$  ns. This relaxation was possible because differences between delay units tended to be unrelated and gave a reasonable performance with a tolerable pattern occasionally visible on the converted picture.

## 6. Conclusions

Two forms of active, adjustable equaliser have been developed in order to correct the amplitude/frequency and

group-delay/frequency response of the delay units used in field-store standards converters. Apparatus has also been developed to enable the adjustment to be carried out empirically to the accuracy demanded by a target specification.

The equalisers have been used in two standards converters which have been made and used within the BBC and also in other converters made by licensed manufacturers for other broadcasting organisations. They have proved satisfactory in operation and have given reliable service.

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